ACOUSTIC DETERMINATION OF NEAR-SURFACE SOIL PROPERTIES

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ABSTRACT

The state of the ground can change dramatically in response to changing meteorological influences and physical disturbances of the ground (e.g. tilling) that are important to many civilian and military activities. Permeability is the fundamental parameter of a porous media that controls whether a surface is an acoustically hard one, through which fluids may not easily penetrate, or conversely a more transparent surface, across which gas and water may readily move. Permeability is the property that controls pressure-driven processes including rain infiltration in soils, surface-atmosphere gas exchange, and acoustic response of the ground. In this paper we describe results of preliminary field tests of the acoustic response of a sand surface under several conditions of moisture and disturbance. We compare these measurements to results of our theory by which a point acoustic source can be used to remotely determine the soil permeability on scales from centimeters to tens of meters across the ground surface. In addition to acoustic means of determining the permeability, we also make a number of direct, co-registered measurements of permeability for comparison.

1. INTRODUCTION

Laboratory measurement techniques for determining permeability of porous media exist for centimeter-scale samples (e.g. Albert et al, 200), and field “slug tests” are commonly used for groundwater hydrology and deep infiltration (e.g. Bouwer, 1978). Yet for many hydrological and military applications, knowledge of permeability is needed on lateral scales up to tens of meters, and on vertical scales of less than a meter. In porous media, permeability is the material parameter that controls pressure-driven processes, for example the passage of an acoustic (pressure) wave through the medium, the flow of gases between the soil and the atmosphere, and the infiltration of rain water or other liquid into the soil. Previous measurements relating to fluid flow through soil have typically been done as "point"-type measurements with permeameters that measure fluid flow and pressure drop across a sample of the material; multiple ways of doing this are described in Dullien (1979). In the acoustics research community, previous outdoor acoustic measurements have determined empirical factors that relate to the effective flow resistivity and relative permeability (e.g. Cramond and Don, 1985; Attenborough,1992; Albert, 2001, Sabatier et al, 1990, Moore et al 1992). However, because these factors contain dimensionless, model-dependent scaling factors, the absolute permeability on scales of one to tens of meters over shallow depths is still unknown. One reason this is the case is because there is no well-documented non-intrusive means of measuring permeability across an expanse of the near-surface ground (top ten cm over a span of many meters). In this paper we describe field tests of the acoustic response of a sand surface under several different conditions of moisture and disturbance. We compare the measurements in our theory to determine permeability based on the acoustic response,. In addition, we also make a number of direct, co-registered measurements of permeability for comparison with the acoustically-determined permeability.

2. BACKGROUND

There are a variety of techniques for measuring permeability of cm-scale samples (e.g. Dullien, 1979; Albert et al, 2000). Sample-scale air permeability measurements can be made in the field and can be quantitatively related to saturated hydraulic conductivity (Loll, 1999) to within natural variability in soil hydraulic conductivity

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field measurements. However, it is labor intensive and it is often difficult to get an undisturbed sample; this is important because the nature of the interconnected pore space controls the permeability. Air permeability measurements on samples from structured soil with samples of different sizes (100 cm^3 and 3140 cm^3) show that small samples generally yielded lower values and a higher variability in permeability than larger samples (Iversen et al, 2001). This implies that correlation in permeability measurements across a range of scales will depend on the degree of soil structure or layering in the sample. Mallants et al (1996) found that macropores and small sampling volume both contribute to spatial variability in permeability measurements at the cm scale. Air permeability measurements of cm-scale samples in an undisturbed constructed field of sandy loam in Japan showed spatial correlation, and measurements on larger samples (3140 cm^3) were similar, indicating this site had little small-scale heterogeneity; however, measurements taken 4 months later show that tilling and precipitation caused a significant increase in permeability (Poulsen et al, 2001). Heterogeneity in soil moisture at a flat silt loam site was spatially dependent over a distance of 0.5m, but maximum variances increased linearly with decreased mean soil moisture as the soil dried (Melloh et al, 2005), hinting that correlation lengths may reflect soil properties but variances indicate moisture level. Higher near-surface permeability permits a spatially variable response to microtopographically focused infiltration of surface water (Keller et al, 1988). In natural conditions, spatial heterogeneity or lack thereof varies from site to site, for example, field measurements including salinity in Iran (Hajrsuliha et al, 1980) show some site-dependent conditions requiring geostatistical analysis, while nearby others are spatially independent. In studies involving many different soil properties and chemistry, Kravchenko et al (1999) found that multifractal parameters reflected many of the major aspects of soil data variability and provided a unique quantitative characterization of the data spatial distributions.

Considerable attention has been paid to near-surface acoustic-to-seismic coupling for land mine detection (e.g. Xiang and Sabatier, 2002; Valeau et al, 2004; Korman and Sabatier, 2004; Fokin et al, 2006). Those studies investigated the mechanical response of the soil particles to an acoustically-induced seismic wave; the results are relevant to compressional waves in the soil matrix, which is made up of the soil particles. We note that those studies are important but address a different physical phenomenon than the topic of this, our current paper, which concerns compression of the air within the stiff soil matirx. The soil permeability is a measure of the nature of the interconnected pore space in soil, and reflects movement of the fluid within the pore space and not the compression of the soil matrix.

Many acoustic measurements have been conducted to characterize ground surfaces, but all have stopped short of linking the results with the fundamental soil property of permeability. Empirical factors have been determined for acoustics over porous media (e.g. Albert, 2001; Attenborough, 1992; Don and Cramond, 1985) however these factors, called effective flow resistivities, depend on the particular acoustical model employed and have not been linked to the fundamental material parameter, permeability. In addition, many acoustic models also include dimensionless “shape factors” that are used to adjust the models to agree with measurements. Previous acoustic measurements to determine soil properties determined the relative, not the absolute, flow resistivity or permeability of the soil (Sabatier et al 1990, Moore and Attenborough 1992). Attenborough’s “four parameter” model of ground impedance (1985) is widely used in studies of outdoor sound propagation and is more accurate than the simpler empirical model of Delaney and Bazley (1970), especially at lower frequencies. However Sabatier et al. (1993) have shown that the four parameters are not independent, and Allard has shown how the parameters of this model are related to the DC flow resistivity of the porous material. Variations in the relative permeability are greater by an order of magnitude from model differences.

Typical values of permeability span many orders of magnitude for natural soils, depending on the type of soil. Table 1 shows that coarse gravel, with a typical permeability of 1×10^{-7} m^2, is more than seven orders of magnitude more permeable than silt, which has a typical permeability of 5×10^{-15} m^2.

While it is recognized that the nature of the ground surface impacts atmospheric acoustic wave attenuation, it has often been assumed that pressures due to surface acoustic sources do not induce significant compression of the air in the pore space in the near-surface soil. We showed (Albert et al 2006) that acoustic waves can penetrate into depths of the soil surface at depths that are relevant to trafficability, tilling, and surface-atmosphere gas exchange. In this paper we report on the next step in our research, which is to compare direct measurements of soil permeability to acoustically-determined permeability under several different soil conditions.

3. METHODS

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For this work we have conducted a number of direct measurements of permeability along with co-registered acoustic tests. The field test was conducted at a prepared site in summer in Vermont. A level ground test plot 40m long by 4 m wide was covered by uniform sieved purchased sand 50 cm deep. Testing was done under compacted and tilled sand conditions; for the compacted cases, a Waccer rolling compacter was run for many passes over the sand. A rototiller was used to till the sand over the length of the plot for the tilled case. The dry sand case was done after the plot was formed and before the first rainfall. The wet sand case was perfomed following the dry sand measurements by using a sprinkler to wet the entire plot.

For each experiment, direct measurements of density, and wetness were made using standard techniques at five locations along the fetch and in samples 4 cm deep down to depths of 12 cm total depth in the sand. The permeability was measured using a custom air permeameter that has been well tested at a variety of sites (e.g. Albert et al, 2000), which measures the air flow rate and pressure drop across the sample in Darcy's law to determine permeability.

Broadband acoustic pulses were recorded as they propagated horizontally above the soil surface at the prepared sand site. A handheld .45-caliber blank pistol fired 1 m above the soil surface was used as the source of the acoustic waves. The acoustic pulses were monitored using a linear array of 4.5-Hz Mark Products model L-15B geophones and Globe model 100C low-frequency microphones located at the soil or snow surface at distances up to 30 m away from the source. In addition, two Bruel & Kjaer type 4165 microphones were used to record the source pulse. A Bison model 9048 digital seismograph, triggered by a microphone located near the pistol, was used to record the waveforms at a sampling rate of 5 kHz per channel. The useful bandwidth of the measurements is estimated as 5–500 Hz and is limited mainly by the source output and the high frequency roll-off of the Globe microphones. The field tests were done on windless days so the atmospheric variability did not induce variablility in the acoustic measurements.

Three cases of soil conditions are investigated here: compacted dry sand, compacted wet sand, and tilled wet sand. Measurements were conducted using blank pistol shots, fired 1 m above the ground, and recorded using a microphone on the ground surface 30 m from the source. Three conditions were tested during summer conditions: dry, compacted sand, wet compacted sand, and wet tilled sand. Six shots were analyzed for each case.The measurements followed the same protocol for each test. The sand plot was prepared (compacted or tilled and wetted or not), the microphone arrays were set out, the acoustical measurements were made, and finally the direct measurements of density, permeability, and moisture content were conducted.

In Albert et al, (2006), we described the theoretical foundation by which outdoor acoustics measurements may be used to determine the meter-scale permeability of the ground over which the acoustic source was applied, and also the depth of penetration of the acoustic wave. The acoustical ly-determined permeability that we report here employ that theory.

4. RESULTS

The acoustic waveforms are shown in Figure 1 for a) dry compacted sand, b) wet compacted sand, and c) wet tilled sand. The waveforms measured over compacted sand show very little distortion compared to the original source pulse, while the waveform for propagation over rough sand has been modified extensively through interaction with the rough surface. The resulting

permeability inferred from the acoustic pulses for the dry compacted sand was 1.4 x10-10 m2 with standard deviation 0.2 x10-10 m2. Acoustically-determined permeability for wet compacted sand was 1.0 x 10-10 m2 with standard deviation 0.1 x10-10 m2, and for wet tilled sand was 13 x 10-10 m2 with standard deviation 3.7 x10-10 m2.

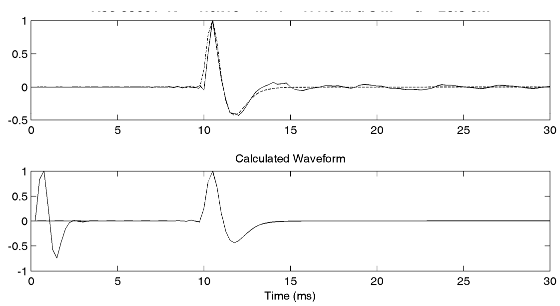

Figure 1. (Top) Comparison between measured (solid line) and theoretical (dashed line) acoustic waveforms for propagation over 30 m of dry sand. The theoretical waveform was determined automatically is shown with the source pulse in the lower panel.

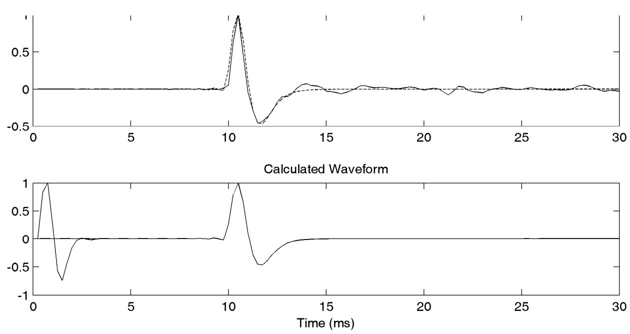

Figure 2. (Top) Comparison between measured (solid line) and theoretical (dashed line) acoustic waveforms for propagation over 30 m of wet sand. The theoretical waveform was determined automatically is shown with the source pulse in the lower panel.

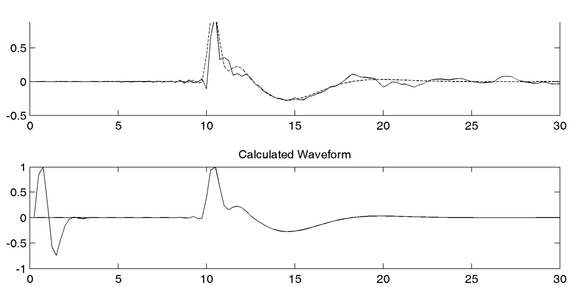

Figure 3. (Top) Comparison between measured (solid line) and theoretical (dashed line) acoustic waveforms for propagation over 30 m of rough (tilled) wet sand. The theoretical waveform was determined automatically is shown with the source pulse in the lower panel.

Direct measurements of permeability were made down along the test plot for each test condition allowing some indication of the variability of the property. For the case of the dry compacted sand, the permeability was 1.45 x10-10 m2 with a standard devation of 1.9 x10-10 m2. For the wet compacted sand, the permeability was 0.41 x10-10 m2 with standard deviation 0.15 . The wet tilled sand had permeability 5.03 x10-10 m2 with standard deviation 4.8 x 10-10 m2. The permeameter has accuracy to within 10% of the measurent; the variability in the measurements above are due to spatial variations in the pore structure across the sand plot.

For both the direct measurements of permeability and the acoustically-determined permeability, in compacted sand the dry case had larger permeability than the wet case. This is to be anticipated due to the fact that for the wet sand, some of the pore space contains liquid water which reduces the impact of pressure wave propagation through the air in the pore space. Agreement between the direct permeability measurements and the acoustically-determined measurements are very good for compacted wet and dry sand.

For the wet tilled sand, both the direct measurement of permeability and the acoustically-determined permeability were very much larger than for the wet and dry compacted cases. In wet sand, the acoustically-determined permeability is about double that of the direct measurement both for compacted and tilled sand.

Inspection of trends in the groups of individual tests of direct permeability measurements show that there are two groups of clustered values in the tilled sand, indicating that it is possible that the tilling did not uniformly “fluff up” the sand along the plot. The direct measurements of permeability in compacted sand do not show any horizontal trends in permeability variability, indicating that the compaction technique

provided a more uniform condition along the fetch of the test plot than was achieved with the tilling.

CONCLUSIONS

Preliminary field tests of the acoustic response of a sand surface under several conditions of moisture and disturbance show that under compacted sand conditions, impacts of soil moisture is detectable both from acoustically-determined and direct measurements of permeability. These differences are very small, however, when compared to differences between compacted sand and tilled sand. For both acoustically-determined and direct measurements of permeability, the tilled sand had much greater permeability than the compacted case as anticipated. These preliminary results show promise for acoustically-determined permeability assessment of ground conditions in situations where more rapid assessment of the permeability is needed than could be acquired through direct measurements.

In continuing research, we will build upon these investigations to non-intrusively measure the effects of soil moisture and spatial variability in soil properties, with comparison to co-located direct measurements. Non-intrusive measurement of permeability in the near-surface soil can provide a leap-ahead that provides the means for investigating a range of problems, including the state of the ground in response to changing meteorological influences and spatial variability in soil properties, which are important to many civilian and military applications.

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